Hazard Calculations Tutorial using ANSI Z136.1 (2014)

- Major changes to MPE
- and Classification limits

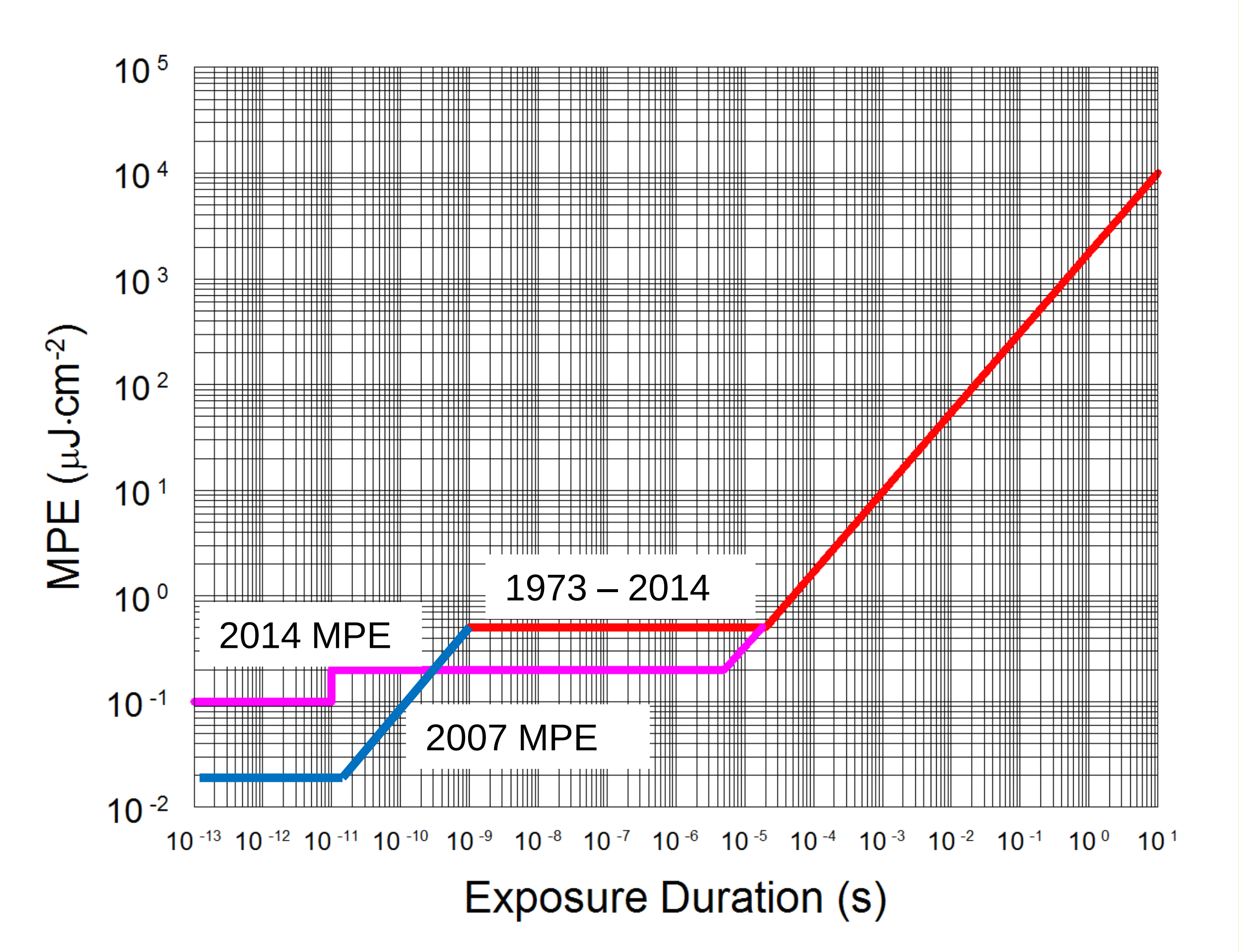
Wes Marshall

Outline

- Changes to Single Pulse MPEs
- Changes in the 1200 to 1400 nm region
- Changes to extended source MPEs
- Multiple pulse MPEs (ANSI and IEC)
- Example: Repetitively pulsed system (1350 nm)
  - Diffuse reflection from rectangular extended source with pulse width longer than t_{min}
- Improving your calculation ability

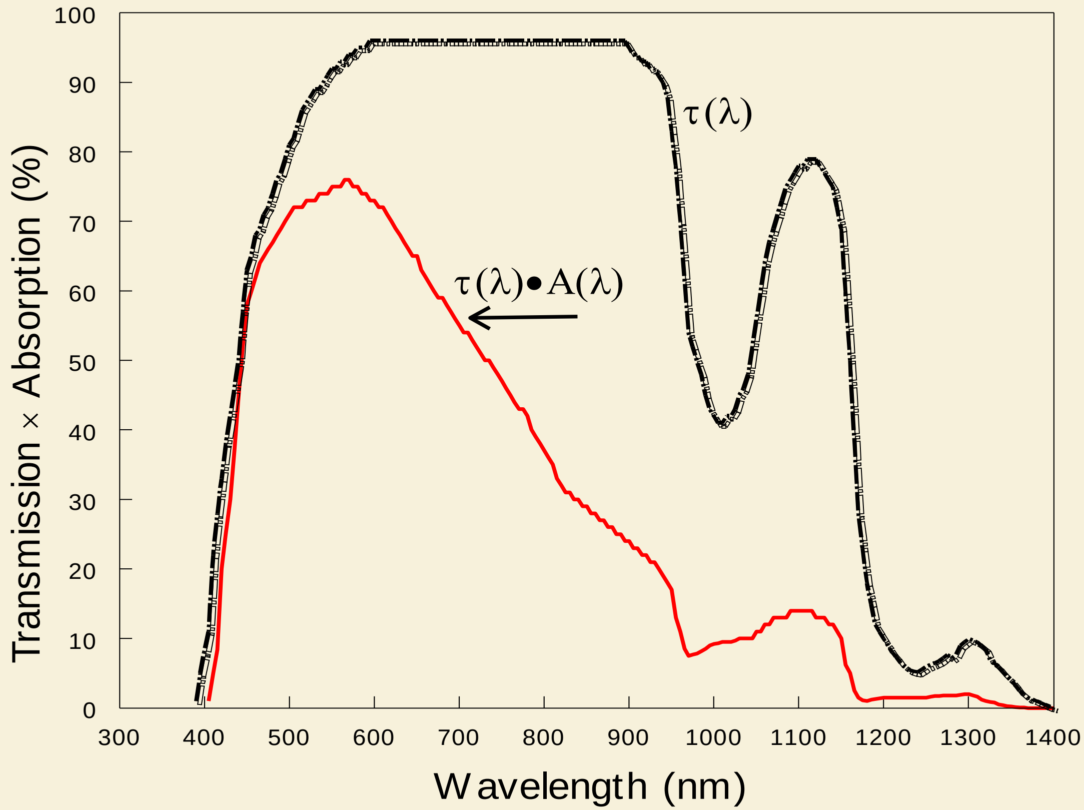
Single Pulse MPE (visible)

- Red line:
- Same MPE from 1973 – 2014 (1 ns to 10 s)
- Blue line:
- MPE for pulses less than 1 ns added in 2000
- 2014 MPEs
  - < 1973 MPE (*t* < 18 μs)
  - > 2007 MPE (*t* < 300 ps)



Wavelength Dependence

- Spectral properties of the ocular media and retina*
- Three Factors affect retina:
  - – Transmission
  - – Absorption
  - – Focus
- $\tau(\lambda) \cdot A(\lambda)$ formed basis for C_A and C_C corrections



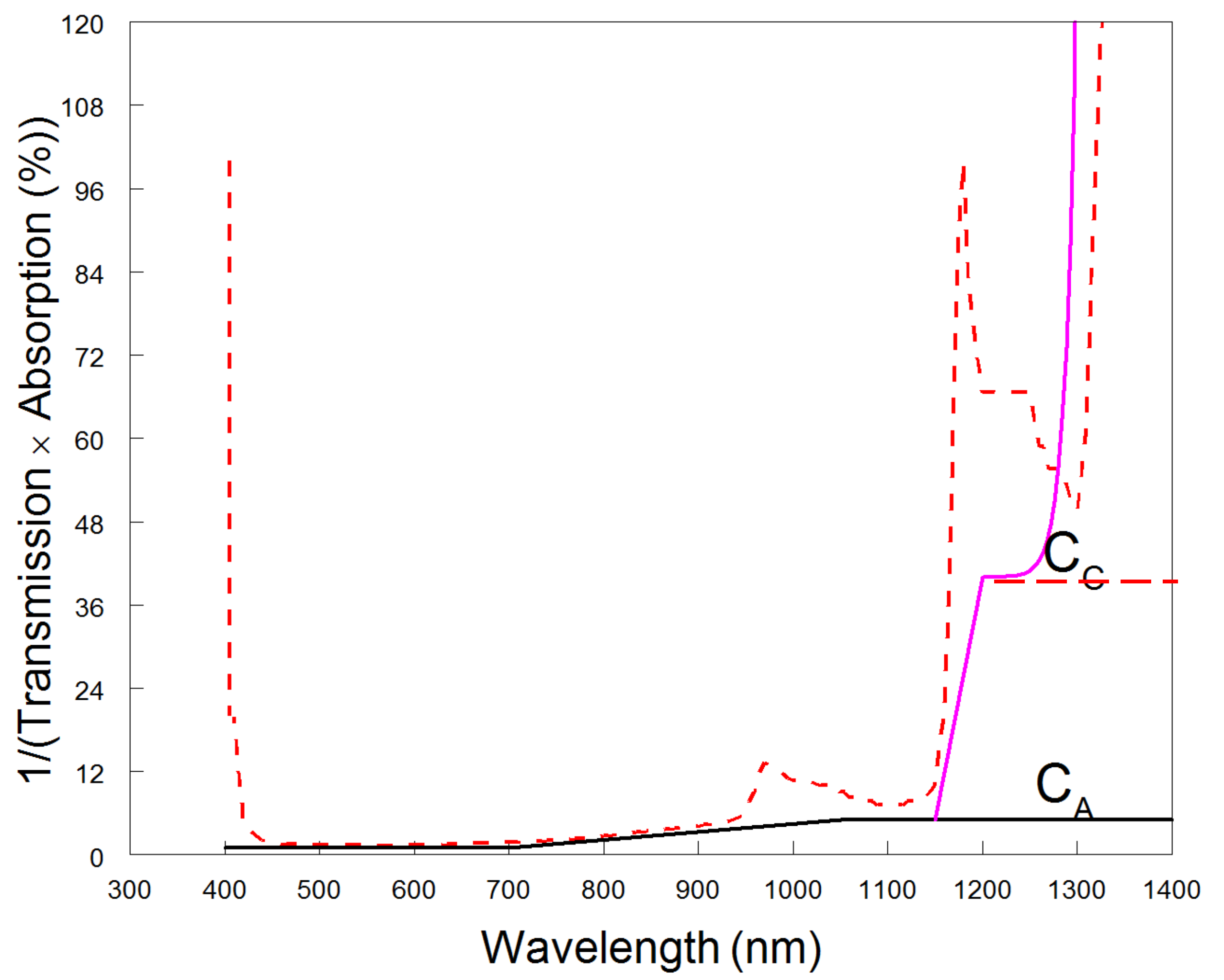
*Ocular specular characteristics as related to hazards from lasers and other light sources, *Am. J. Opthathl, 66, 15-20 (1968)*

Wavelength Factors

- 400 – 700 nm: no wavelength correction
- 700 – 1050 nm: C_A increase from 1 to 5× at 1050 nm
- 1050 – 1150 nm – 10× increase for pulses t < 18 µs
  5× increase for t > 50 µs
- 1150 – 1200 nm – C_C additional increase from 1 to 8
- 2007 Correction to MPEs compared to visible MPE
- 1200 – 1400 nm -- 80× increase for pulses t < 18 µs
  40× increase for t > 50 µs
- 2014 Increased MPE for 1200 to 1400 nm

Revision in C_C Correction Factor

- Change in C_C based on biological data
- Possibly due to difference in focal point (away from RPE)
- Dual limit required for corneal exposure 1200 to 1400 nm

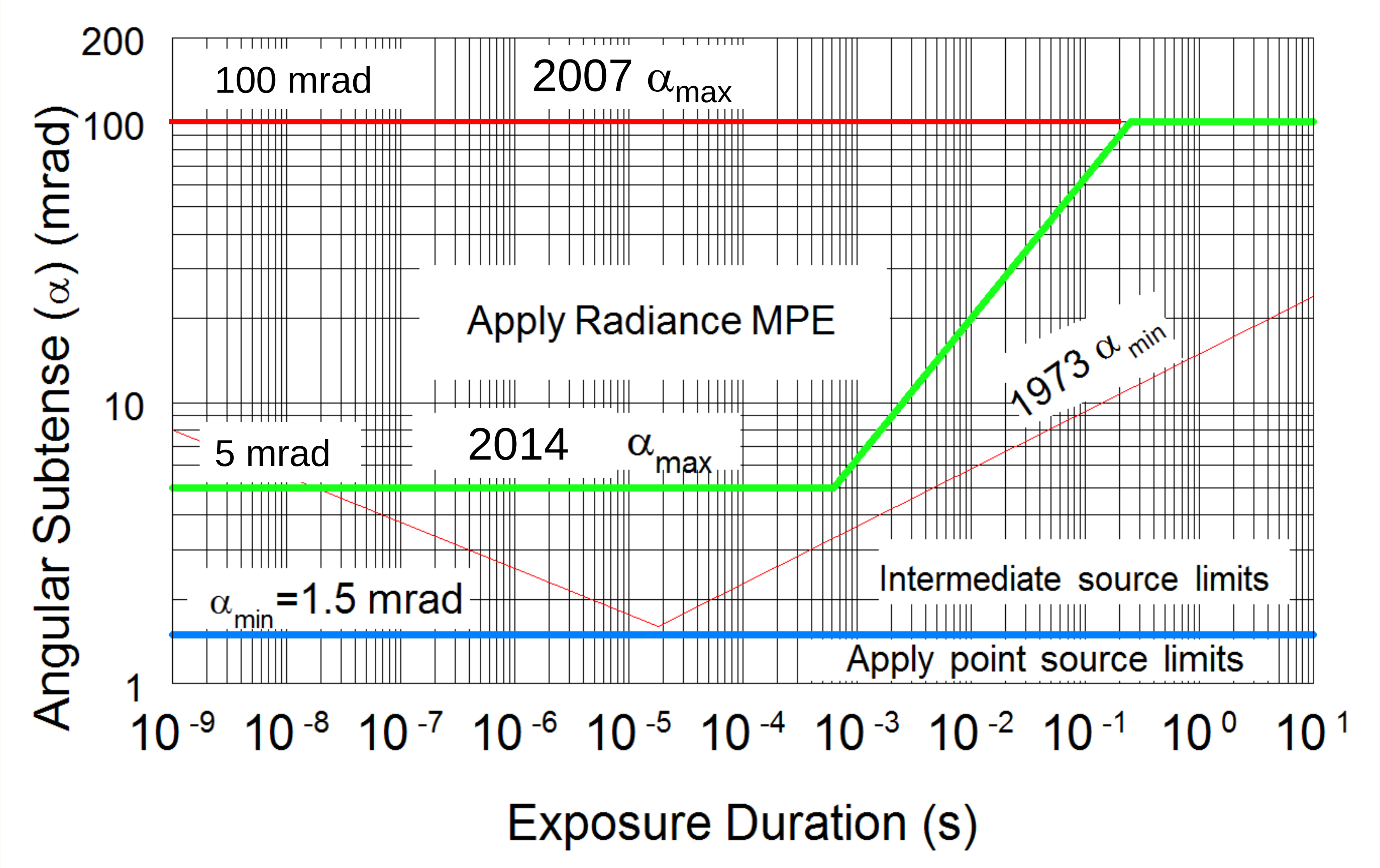


8/28/2014

MPEs (1200 to 1400 nm)

- Increase in C_C from 8 to 9 for 1200 to 1250 nm
- Huge increase in C_C for 1250 to 1400 nm (retinal)
- Offset by dual limits for 1200 to 1400 nm (cornea)
- New corneal MPEs for 1200 to 1400 nm
- For example: pulses of $t < 1$ ms
  - 2007 MPE for 1400 nm was 100 mJ/cm^2
  - 2014 MPE for 1400 nm is 300 mJ/cm^2
  - 2014 MPE for 1200 nm is 30 J/cm^2
- Corneal limiting aperture varies from 1 to 3.5 mm

2014 Extended Source Limits



8/28/2014

Time varying $\alpha_{max}(t)$

- $\alpha_{max}(t)$ = 5 mrad for t < 625 µs
- $\alpha_{max}(t) = 200\ t^{0.5}$ mrad for 625 µs < t <0.25 s
- $\alpha_{max}(t)$ = 100 mrad for t > 0.25 s
- ANSI Z136.1 – 1973 through 1980
  - α_{min} and α_{max} were the same: V shape (t < 10 s)
- ANSI Z136.1 – 1986 through 2014
  - α_{min} varied from 1.5 to 11 mrad (1986 – 1993)
  - α_{min} = 1.5 mrad (2000 – 2014)
  - α_{max} = 100 mrad for all exposure durations (2007)

Repetitive Pulse Limits

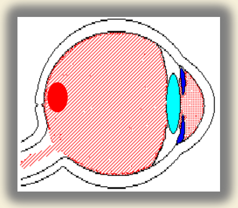
- ANSI Z136.1 (1993 - 2007):
  - $C_P = n^{-0.25}$ for all lasers (thermal MPE for eye)
- ANSI Z136.1 (2014) – No C_P for:
  - Point Sources, skin, or corneal exposure (UV & IR)
  - Short pulse lasers ($t < 5$ µs)
  - Large extended sources ($\alpha > 100$ mrad)
- For other extended sources:
  - $C_P = n^{-0.25}$, limited to 0.4 for $\alpha < \alpha_{max}$ (40 pulses)
  - $C_P = n^{-0.25}$, limited to 0.2 for $\alpha < 100$ mrad (625 p.)
- Applies to individual pulses or pulse groups

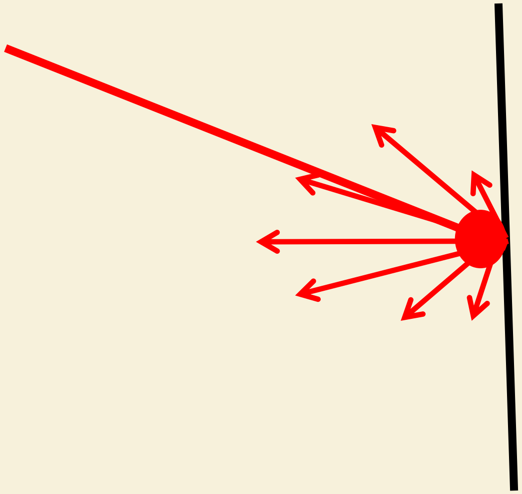
Multiple pulses IEC 60825-1 (2014)

- For time base < 0.25 s and $t < t_{min}$: $C_P = 1.0$
- For time base > 0.25 s and $t < t_{min}$:
  - $C_P = 1.0$ for $N \leq 600$
  - $C_P = 5 \times N^{-0.25}$ for lasers (N> 600 & retinal hazard)
  – Applies to individual pulses separated by $t > t_{min}$
- For $t > t_{min}$ (same as ANSI Z136.1-2014)
- $\alpha \leq 5$ mrad $C_P = 1.0$
- 5 mrad $< \alpha \leq \alpha_{max}$ $C_P = N^{-0.25}$ (N<40) (>0.4)
- $\alpha > \alpha_{max}$ $C_P = N^{-0.25}$ (N<625)(>0.2)
- For $\alpha > 100$ mrad $C_P = 1.0$

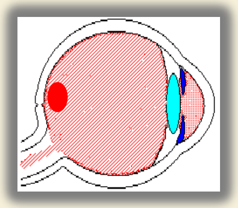
Extended Source Viewing

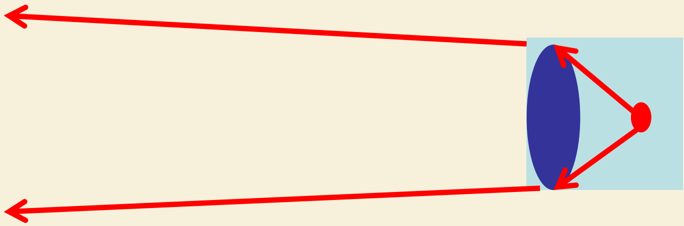
- Two main scenarios:
- Diffuse reflection





- Diode laser





- Both produce a larger retinal image than point source

Extended Source Correction

- In principal, no changes to calculation of C_E
- Changed values of C_E attribute to α_{max} (t), whereas α_{max} was a constant 100 mrad in previous versions
- The symbol α_{max} was created with forethought that it might become a function in future versions
- Circular Sources:
  - $C_E = 1.0$ for $\alpha < \alpha_{min}$
  - $C_E = \alpha / \alpha_{min}$ for $\alpha_{min} < \alpha < \alpha_{max}$
  - $C_E = \alpha^2 / (\alpha_{min} \cdot \alpha_{max})$ for $\alpha > \alpha_{max}$

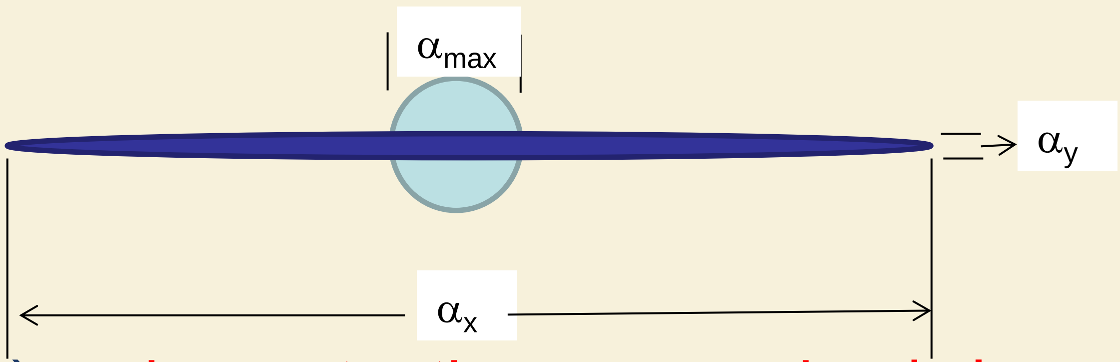
8/28/2014

Rectangular Sources

- Rectangular and elliptical sources are handled in exactly the same way as in previous versions
- ANSI Z136.1 standard unclear on the method
- Elongated Sources (rectangular or elliptical)
  - $C_E = 1.0$ for $\alpha_x < \alpha_{min}$ and $\alpha_y < \alpha_{min}$
  - $C_E = (\alpha_x + \alpha_y)/(2 \cdot \alpha_{min})$ for $\alpha_x < \alpha_{max}$ and $\alpha_y < \alpha_{max}$
  - $C_E = \alpha_x \cdot (\alpha_{max} + \alpha_y)/(2 \cdot \alpha_{min} \cdot \alpha_{max})$ for $\alpha_x > \alpha_{max}$ and $\alpha_y < \alpha_{max}$
  - $C_E = (\alpha_x \cdot \alpha_y)/(\alpha_{min} \cdot \alpha_{max})$ for $\alpha_x > \alpha_{max}$ and $\alpha_y > \alpha_{max}$
- α is set to ≥ 1.5 mrad if smaller
- $\alpha_x > \alpha_y$ by definition

Elongated extended source cases

- 1) α_x is less than α_{max} and α_y is less than α_{max}



Arithmetic mean

$$C_E = \frac{(\alpha_x + \alpha_y)}{2 \times \alpha_{min}}$$

- 2) α_x is greater than α_{max} and α_y is less than α_{max}

$$C_E = \left(\frac{\alpha_x}{\alpha_{max}}\right) \times \frac{(\alpha_{max} + \alpha_y)}{2 \times \alpha_{min}} = \frac{\alpha_x(\alpha_{max} + \alpha_y)}{2 \cdot \alpha_{min} \cdot \alpha_{max}}$$

Eliminate portion outside of α_{max} cone through increase in C_E

- 3) α_x is greater than α_{max} and α_y is greater than α_{max}

$$C_E = \left(\frac{\alpha_x}{\alpha_{max}}\right) \times \left(\frac{\alpha_y}{\alpha_{max}}\right) \times \frac{(\alpha_{max} + \alpha_{max})}{2 \times \alpha_{min}} = \frac{\alpha_x \times \alpha_y \times (2 \times \alpha_{max})}{2 \cdot \alpha_{min} \cdot \alpha_{max}^{2}} = \frac{\alpha_x \cdot \alpha_y}{\alpha_{min} \cdot \alpha_{max}}$$

Summary of Revised Exposure Limits

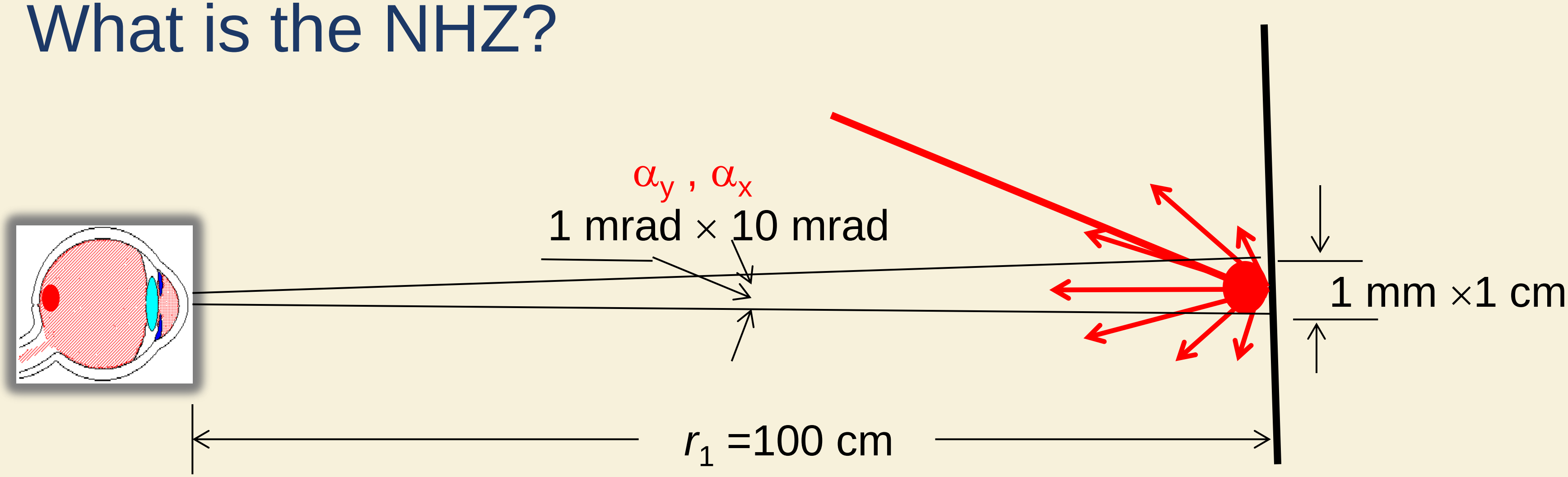
- Elimination of repetitively pulsed correction factor in ANSI Z136.1 except for some extended source lasers
- Reduction in single pulse MPE by 2.5 times for many lasers in retinal hazard region ~ (0.3 ns < *t* < 5 µs)
- Increased MPE for ultrashort pulsed lasers (*t* < 0.3 ns)
- Elimination of C_A wavelength correction factor for short pulsed lasers less than 20 ps
- Increase in C_C correction factor for 1200 to 1400 nm
- Changes to extended source MPEs
- Dual retinal/corneal limits for 1200 to 1400 nm

MATH

- Mental
- Abuse
- To
- Humans

Example Calculation

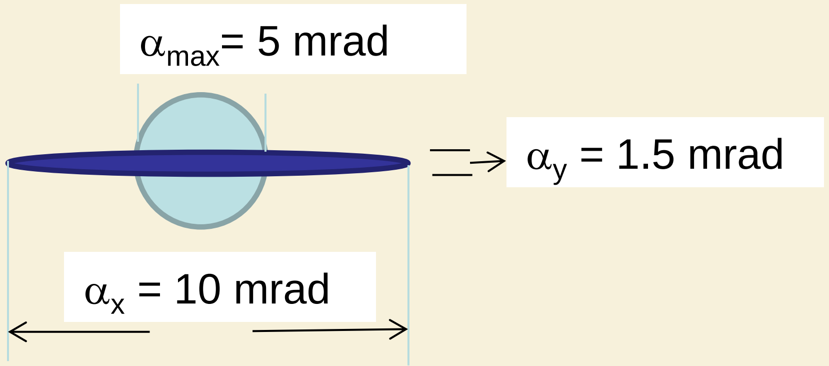
- Laser: 1350 nm, 45 μs pulse width, PRF =1000 Hz
- Power = 100 W, T_{max}= 100 s
- Beam size on Target: D_L = 1 mm × 1 cm
- r_1 = 100 cm
- Is there a hazard from the diffuse reflection?
- What is the NHZ?



8/28/2014

Determine the MPE

- Rules 1, 2, and 3 must be considered (t = 45 μs)
- t_{min} = 13 μs ($t > t_{min}$)
- α (two parts) = (1 cm×10 cm)/100 cm = 1 × 10 mrad
- α_x is the long dimension, α_y is the smaller (by def'n)
- α_y increased to 1.5 mrad for calculation of C_E
- α_{max} = 5 mrad for t < 625 μs



8/28/2014

Determine the MPE (Rule 1)

- Rule 1:
  - – $MPE_{SP} = 9 \times (45 \times 10^{-6})^{0.75} \times C_C \times C_E$ mJ·cm^{-2}

$$C_E = \frac{\alpha_x}{\alpha_{max}} \times \frac{(\alpha_{max} + \alpha_y)}{(2 \times \alpha_{min})}$$

First part eliminates contribution outside of α_{max}

  - – $C_E = (10/5) \times [(5 + 1.5)/(2 \times 1.5)] = 4.33$
  - – $C_C = 8 + 10^{0.04(\lambda-1250)} = 8 + 10{,}000 = 10{,}008$
  - – *MPE/pulse* = 214 mJ·cm^{-2}
  - – *MPE:E* = 214 mJ·cm^{-2} × 1000 Hz
  - – *MPE:E* = 214 W·cm^{-2}

8/28/2014

MPE (Rule 2)

- T_2 is determined based on the average source size
- α_x and α_y are limited to $\alpha \geq \alpha_{min}$ and $\alpha \leq 100$ mrad
- α (average) = (10 + 1.5)/2 = 5.75 mrad
- $T_2 = 10 \times 10^{(5.75-1.5)/98.5} = 11.04$ s

$$C_E = \frac{\alpha(average)}{\alpha_{\min}}$$

  - $MPE_{group} = 9\times10^{-3} \times (11)^{0.75} \times C_C \times C_E$ J·cm^{-2}
    - C_E = (5.75 mrad) /(1.5 mrad) = 3.83
    - C_C = 10,008
    - n = 1000 Hz ×11 s = 11,000 pulses

$\alpha_{max}(t)$= 100 mrad for t > 0.25 s

  - *MPE/pulse* = 2.08 kJ·cm^{-2}/(11,000) = 189 mJ·cm^{-2}
  - *MPE:E* = 189 mJ·cm^{-2} × 1000 Hz
  - *MPE:E* = 189 W·cm^{-2}
- Rule 2 is more restrictive than Rule 1

8/28/2014

MPE (Rule 3)

MPE (Rule 3)

- MPE based on t = 45 μs
- MPE_{SP} = 214 W·cm^{-2}
- α(average) = 5.75 mrad
- *MPE* = 214 mJ·cm^{-2} 0.2
- *MPE:H* = 42.8 mJ·cm^{-2}
- 42.8 mJ·cm^{-2} × 1000 Hz
- *MPE:E* = 42.8 W·cm^{-2}

Factors to be aware of

- Rule 1 MPE = 214 W·cm^{-2}
- Rule 3 applies since $t > t_{min}$
- α(average) used in computing T_2 is also used for C_P
- α_{max}= 5 mrad (t < 625 μs)
- α(average) > α_{max}
- n = 11,000 pulses
- C_P = 0.2 for n > 625 pulses
- C_E was not based on α(average)

8/28/2014

Determine the Exposure at 100 cm

- Determine the exposure at 100 cm from the diffuse surface:

$$E = \frac{\rho_\lambda \times \Phi \times \cos\theta_\upsilon}{\pi \times r_1^2}$$

- Worst case: ρ_λ = 1.0, θ_υ = 0°

$$E = \frac{(1.0)\times(100\,\mathrm{W})\times(1)}{\pi\times(100\,\mathrm{cm})^2} = 3.18\,\mathrm{mW}\cdot\mathrm{cm}^{-2}$$

Retinal MPE

Rule 1	Exposure	%
MPE/pulse = 214 $mJ \cdot cm^{-2}$		
MPE:E = 214 $W \cdot cm^{-2}$	*MPE:E* = 3.18 $mW \cdot cm^{-2}$	< 0.1
Rule 2		
MPE/pulse = 189 $mJ \cdot cm^{-2}$		
MPE:E = 189 $W \cdot cm^{-2}$	*MPE:E* = 3.18 $mW \cdot cm^{-2}$	< 0.1
Rule 3		
MPE/pulse = 42.8 $mJ \cdot cm^{-2}$		
MPE:E = 42.8 $W \cdot cm^{-2}$	*MPE:E* = 3.18 $mW \cdot cm^{-2}$	< 0.1

Rule 3 provides most restrictive retinal MPE

Corneal MPE (Rule 1)

- Rule 1 (Corneal):
  - $MPE_{SP} = 0.3\ K_{\lambda}\ J{\cdot}cm^{-2}$
  - $K_{\lambda} = 10^{0.01(1400\ -\ \lambda)} = 10^{0.01(1400\ -\ 1350)} = 3.16$
  - $MPE_{SP} = (0.3 \times 3.16) = 949\ mJ{\cdot}cm^{-2}$
  - *MPE:E* $= 949\ mJ{\cdot}cm^{-2} \times 1000\ Hz$
  - *MPE:E* $= 949\ W{\cdot}cm^{-2}$

Corneal MPE (Rule 2)

- Rule 2 (Corneal):
  - *MPE:E* = $(0.03\ K_\lambda + 0.07)\ W \cdot cm^{-2}$
  - $K_\lambda = 3.16$
  - *MPE:E* = $[(0.03 \times 3.16) + 0.07]\ W \cdot cm^{-2}$
  - *MPE:E* = $165\ mW \cdot cm^{-2}$
  - *MPE/Pulse* = $165\ \mu J \cdot cm^{-2}$

MPE compared to Exposure

Retina		Cornea	Exposure	
	Rule 1	Rule 1		%
MPE/pulse	214 mJ·cm^{-2}	949 mJ·cm^{-2}		
MPE:E	214 W·cm^{-2}	949 W·cm^{-2}	3.18 mW·cm^{-2}	< 0.1
	Rule 2	**Rule 2**		
MPE/pulse	189 mJ·cm^{-2}	165 μJ·cm^{-2}		
MPE:E	189 W·cm^{-2}	165 mW·cm^{-2}	3.18 mW·cm^{-2}	1.93
	Rule 3	**Rule 3 (N/A)**		
MPE/pulse	42.8 mJ·cm^{-2}			
MPE:E	42.8 W·cm^{-2}		3.18 mW·cm^{-2}	< 0.1

Corneal MPE (Rule 2) is most restrictive

8/28/2014

MPE Summary

- Rule 3 not considered for corneal exposure
- Rule 3 retinal MPE more restrictive than Rules 1 or 2
- Rule 2 for corneal MPE more restrictive than Rule 1
- Corneal MPE is more restrictive than retinal MPE
- Rule 2 for corneal MPE determines the hazard

Determine the NHZ

- Determine the minimum distance from the diffuse surface where the MPE is not exceeded:

$$r_{NHZ} = \sqrt{\frac{\rho \Phi \cos \theta_{\upsilon}}{\pi \, MPE_{\mathrm{E}}}}$$

- The retinal MPE is a function of both C_E and T_2, both of which are functions of α
- At distances less than 1 m, the retinal MPE increases, but the corneal MPE stays the same
- Therefore, the corneal MPE determines the hazard at distances closer than 1 m as well as at 1 m

Determine the NHZ

- Substituting values:

$$r_{NHZ} = \sqrt{\frac{(1.0)(100\ \mathrm{W})(1.0)}{\pi\left(0.165\ \mathrm{W}\cdot\mathrm{cm}^{-2}\right)}}$$

- r_{NHZ} = 13.9 cm

Calculation Challenges

- Calculations of MPEs for collimated beams will be somewhat simplified due to the elimination of the C_P factor, at least for the ANSI standard
- ANSI Calculations for multiple pulse, extended source lasers is much more complicated due to:
  - Time varying $\alpha_{max}(t)$
  - Changes to C_P calculations
  - Application of C_P to both individual pulses and pulse groups due to time varying C_E
  - Dual MPEs and limiting apertures: 1200 – 1400 nm

Resources

- Appendix B, ANSI Z136.1: Extensive examples in each edition of the Z136 series
- The methods described in the Z136 series have examples and explanation in Appendix B
- Choices for improving your ability with calculations:
  - Study examples in ANSI Z136.1, Appendix B
  - Hire a consultant (especially if your company is at risk)
  - Attend a calculation workshop (Phoenix, Sep 16-17)
  - Use software to assist in your understanding (relying solely on software is not recommended)
  - All of the above (Recommended)

Software

- Software designed for the 2007 ANSI and IEC standards will be ineffective in evaluating lasers according to the new standards
- Significant differences in calculation methods between the old and new standards could lead to confusion
- Software programs that permit calculation by either current or past standards will be desirable since not all organizations will automatically switch to the new versions immediately

LAZAN Premium 6 (RLI))

- Analysis by ANSI 2000, 2007 or 2014, IEC 2007 or 2014
- Comparison of photochemical, thermal, retinal, corneal, and skin
- Choice of ANSI or IEC methods for evaluation or classification
- Results displayed in a variety of units including power through an aperture, irradiance, radiant exposure, radiance, integrated radiance: W/cm^2, W/m^2, J/cm^2, J/m^2, $W/cm^2/sr$, $J/cm^2/sr$, etc.
- Laser data for each evaluated system stored in database
- Ancillary data also stored with each system such as personnel involved (supervisor, LSO, user), location, manufacturer, service provider, links to reports, contracts, or other documents
- Detailed reports and graphs of system parameters and analysis
- Preloaded examples from 2007 and 2014 ANSI standards and draft ANSI Z136.6

Questions

- Any questions on the material covered?
- I will be at RLI's booth this afternoon only to answer specific questions
- At the RLI booth, we are providing a fully functional software program that will enable you to follow detailed calculation methods of each example in the ANSI Z136.1 (2007 or 2014), the draft ANSI Z136.6, and your individual systems (95% of examples in the ANSI Z136.1 are included)
- The software will breeze through the example from this presentation or the ANSI examples (ask for the secret)